Modeling Weather-Crop Growth Relationships in Taro

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ABSTRACT

Phenological development of the crop is important for predicting biomass production and scheduling harvest in taro [*Colocasia esculenta* (L.) Schott]. Selecting plants with high harvest index (HI) can increase corm yield in taro. Planting time, however, affects the response of HI in taro. Data from six planting months of field-grown taro across a 3-year period were collected to develop a suitable and simple approach for modeling the seasonal variation of HI in taro under a changed climate. The calendar days after planting (DAP) and growing degree days after planting (GDD) were included as independent variables to analyze the three-phase piecewise linear function with HI. The equations describe the responses of HI during the three periods: the lag phase, linear increase phase, and maturity stage, respectively. Piecewise linear functions based on either DAP or GDD fitted well. The response during the linear increase phase of HI was most important for final HI, which depended on the temperature and solar radiation during the vigorous top-growth stage. This linear increase phase was, however, more stable across years for the GDD model. Moreover, the model based on GDD was superior to DAP for explaining the seasonal variation of HI in taro. In GDD model, taro planted in January and March had a long duration of linear increase in HI that favored yield at maturity, although their dry matter production in the aboveground vegetative organs might be damaged by typhoons during the vigorous top-growth stage. Both the low rate and short duration of linear increase in HI caused low yield for the July crop. These results indicate that the GDD model is a useful approach for determining weather-crop growth relationships in taro. Information gained in this study should help relate phenological responses to seasonal variations in taro.

Key words: Taro (*Colocasia esculenta)*, Harvest index, Phenological model, Growing degree days, Seasonal variation, Climatic factors.

芋之天氣-作物生長關係模式化

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摘要

芋植株的生理發育對其物質生產預測及收穫計畫非常重要。而提高收穫指數，可期獲有高的球莖產量，惟不同種植期會影響芋之收穫指數的反應表現。因此，本研究利用6 個種植月份進行連續 3 週年的水田栽培試驗，發展出一個最適且簡易的動態模式，以瞭解水芋收穫指數在氣候改變下的季節性變異。模式呈一種連續的三相分段線性函數，用以描述收穫指數在遲滯期、線性增加期及成熟期之三個直線階段的表現。無論是採用種植後日曆天數(DAP)或生育度數(GDD)作為自變數，所有種植期下的水芋收穫指數都能與模式良好配合。根據動態模式之解析，其中以收穫指數線性增加期的反應受到栽培

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投稿日期：2004 年 7 月 19 日
接受日期：2005 年 1 月 4 日
作物、環境與生物資訊 2:61-72 (2005)
Crop, Environment & Bioinformatics 2: 61-72 (2005)
189 Chung-Cheng Rd., Wufeng, Taichung Hsien 41301, Taiwan (ROC)

季節之氣象變化影響最大，尤其是溫度及日照，故造成最終收穫指數在不同種植期之間的季節性差異。GDD 模式在不同年度間最穩定，且用以解釋水芋收穫指數之變化趨勢的效能優於 DAP 模式。從 GDD 模式得知，雖然一月及三月種植期的水芋植株在其地上部快速生長階段可能遭受到颱風侵襲之傷害，但因為其收穫指數線性增加期的持續時間較長，故有利於最終的收穫產量；七月種植期的水芋收穫指數線性增加期的增加速度較慢且持續時間較短，故造成低產。由此可知，以 GDD 所建立的水芋收穫指數動態模式，能有效地描述及預測天氣對芋作物生長的影響關係，據此所獲資訊能有利於解析水芋對季節性變異的生理反應。

關鍵詞：芋、收穫指數、生物氣候模式、生育日數、季節性變異、氣候因子。

INTRODUCTION

Taro [*Colocasia esculenta* (L.) Schott] is a wetland crop cultivated in many tropical and subtropical areas of the world and is known tolerant to a range of climate conditions. While taro can be grown throughout the year in Taiwan, the time to reach maturity and attain good yields will vary with planting seasons. Prediction of biomass production is important for scheduling harvest and milling operations (Shih and Snyder 1984, Mohankumar and Sadanandan 1990, Goenaga 1995). The leaf, petiole and corm of taro are all edible, whereas, corm is the major market portion. Corm yield might be increased by selecting plants with high harvest index (HI) in taro (Chan 1996). Harvest index is the ratio of economic yield to biological yield and is the indicator frequently used to describe the accumulation and redistribution of assimilates to achieve final yield (Donald and Hamblin 1976, Bange *et al.* 1998). Both biological yield and HI in taro are sensitive to environmental conditions during the vigorous top-growth and rapid corm-bulking stages (Goenaga 1995, Chan 1996). Chan (1996) found that corm dry weight was associated with an increase in HI up to harvest stage or 9 to 10 months after planting. When total dry weight was held constant, HI was positively correlated with corm dry weight. The responses of linear increase in HI appeared to be most important for final HI. The linear increase in HI was, however, sensitive to climatic factors and varied with planting seasons (Lu *et al.* 1999).

Chan *et al.* (1998) found that the primary factor governing taro growth rate was temperature. The effect of temperature on development rate has been described using a thermal-time concept, which assumes that phenological development is constant per degree of temperature between a base temperature and an upper threshold temperature, above and below which the development rate is zero. Although temperature and photoperiod interact to influence crop development, thermal models are generally accepted as adequate at predicting plant growth and development (Mederski *et al.* 1973, Kiniry *et al.* 1983, Daughtry *et al.* 1984, Russelle *et al.* 1984, Stewart *et al.* 1998, Yan and Hunt 1999). Many different thermal indices have been used to predict dates of flowering and maturity in crops (Cross and Zuber 1972, Coelho and Dale 1980, Mitchell *et al.* 1997, Stewart *et al.* 1998). The most commonly used index is growing degree days (GDD). The GDD unit for a given day is defined as the difference between the daily mean temperature and a growth threshold temperature (Gilmore and Rogers 1958, Cross and Zuber 1972). A GDD index is obtained by summing the daily GDD from planting to the phase of plant ontogeny desired, usually flowering or maturity in many cases. With the GDD method, there is a linear relationship between GDD and rate of plant development (Wang 1960). The practical impact of using GDD is considerable (Ritchie and NeSmith 1991). For example, GDD can be used to classify plants for their flowering dates or length of cycle, to estimate harvest maturity, and to predict the duration between two developmental stages (Bonhomme 2000).

To find better ways of developing a dynamic model of HI in taro, this study quantified the relationship of calendar days after planting (DAP) and GDD to HI in taro and to compare their ability to explain seasonal variation in the linear increase of HI. Based on these models, we predicted the onset and cessation of linear increase in HI, investigated the seasonal variation of parameter estimates, and examined their effects on final HI.

MATERIALS AND METHODS

Wetland Binroshin taro [*Colocasia esculenta* (L.) Schott], an important local variety in Taiwan, was used as material. Experiments were conducted from January 1994 to September 1997 to cover six planting months (seasons) across three years at Taiwan Agricultural Research Institute (TARI) in Taichung Hsien, Taiwan. Planting months were January, March, May, July, September, and November. Seed corms were planted in a randomized complete block design with four replicates for all of the experiments. Seed corms were spaced at 0.70 by 0.30 m with 200 plants per plot. Routine field management practices were followed. Twelve plant samples were taken from each plot at monthly intervals from planting to harvest. The matured plants were harvested at 9 or 10 months after planting. Daily mean temperature, monthly solar radiation, monthly precipitation and typhoon data at TARI were also collected during the experimental periods.

Harvest index was determined from each sample taken after planting in all experiments as the ratio of corm dry weight (economic yield) to dry weight of the aboveground vegetative organs and corm (biological yield) (Chan 1996). The HI data, calculated from each plot (six planting months by three years), were plotted against DAP and GDD to obtain information on the lag phase, the phase of linear increase, and the cessation of linear increase. For each model, a three-phase piecewise linear function (as shown in Fig. 1) was fitted using weighted triple exponential functions in SigmaPlot Version 4 (SPSS 1997a, 1997b):

$$\mathrm{HI} = \begin{cases} f_1(t) = [x_1(T_1-t)+x_2(t-t_1)] \,/\, (T_1-t_1), & \text{if} \quad t_1 \le t \le T_1 \\ f_2(t) = [x_2(T_2-t)+x_3(t-T_1)] \,/\, (T_2-T_1), & \text{if} \quad T_1 \le t \le T_2 \\ f_3(t) = [x_3(t_4-t)+x_4(t-T_2)] \,/\, (t_4-T_2), & \text{if} \quad T_2 \le t \le t_4 \end{cases} \tag{1}$$

where HI is harvest index as modelled by three separate equations; f_1, f_2, f_3, representing three line segments joined at their endpoints as shown Fig. 1. Equations f_1, f_2, and f_3 describe the responses of HI during the three periods: the lag phase, linear increase phase, and maturity stage, respectively. The variable t is the time after planting, using DAP or GDD. This model has eight parameters: t_1 is the start of the lag phase; T_1 is the time at the intersection of f_1 and f_2, i.e., the start of the linear increase phase; T_2 is the time at the intersection of f_2 and f_3, i.e., the cessation of the linear increase phase; t_4 is the time at harvest; x_1 is the HI value at t_1; x_2 is the HI value at the intersection of f_1 and f_2; x_3 is the HI value at the intersection of f_2 and f_3; x_4 is the HI value at t_4.

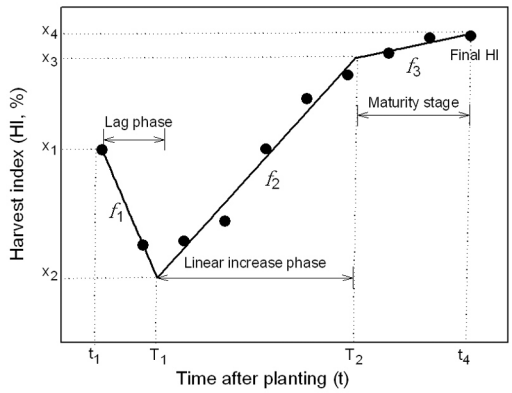

Fig. 1. A three-phase piecewise linear function fitted to harvest index (HI) of wetland taro planted in March 1995. The HI is modeled by three separate equations, representing three line segments joined at their endpoints. The equations, f_1, f_2, f_3, describe the responses of HI during the three periods: the lag phase, linear increase phase, and maturity stage, respectively. The time parameters, t_1, T_1, T_2, and t_4, represent the start of the lag phase, the start of the linear increase phase, the cessation of the linear increase phase, and the time at harvest, respectively. The corresponding HI values at separate times are showed as x_1 for the HI value at t_1, x_2 for the HI value at T_1, x_3 for the HI value at T_2, and x_4 for the HI value at t_4.

Rate and duration for each phase in HI were calculated as follows:

$$\begin{cases} \text{Rate of the lag phase in HI} = (x_2 - x_1) / (T_1 - t_1) \\ \text{Rate of the linear increase phase in HI} = (x_3 - x_2) / (T_2 - T_1) \\ \text{Rate of the maturity stage in HI} = (x_4 - x_3) / (t_4 - T_2) \end{cases} \tag{2}$$

$$\begin{cases} \text{Duration of the lag phase in HI} = (T_1 - t_1) \\ \text{Duration of linear increase phase in HI} = (T_2 - T_1) \\ \text{Duration of the maturity stage in HI} = (t_4 - T_2) \end{cases} \tag{3}$$

The GDD index for the period from planting to harvest was defined as:

$$\Sigma GDD = \Sigma\{[T_{max} + T_{min}]/2 - T_b\} \quad (4)$$

where T_{max} and T_{min} are maximum and minimum air temperatures, respectively, and T_b is the base temperature. When value of daily mean temperature $[(T_{max} + T_{min})/2]$ is less than the base temperature (T_b), GDD equals zero. In this study, GDD was calculated with a base temperature of 17℃, which for taro, was estimated by Lu *et al.* (2001).

The DAP and GDD were used to analyze HI data from the three-year experimental period. For each model, an analysis of variance, with years as blocks, was conducted on the rate and duration of linear increase in HI to make comparisons among planting months. Treatment means were separated by Fisher's protected LSD. Treatments were considered significantly different at $P<0.05$.

RESULTS AND DISCUSSION

Monthly changes in temperature, solar radiation and precipitation at TARI during the 1994-1997 cropping seasons are shown in Fig.2. Patterns of changes in temperature and solar radiation were very similar to each other. Increases in temperature and solar radiation were generally largest in the March to August period. Negative changes of temperature and solar radiation tended to be greatest during the period from October to January. Rainfall in central Taiwan is usually abundant, especially from March to July. Although moisture stress strongly interacted with temperature in plant growth processes, it had little effect on the growth of wetland taro. Typhoons often occur between June and October in Taiwan; yet only strong wind and heavy precipitation associated with typhoons CAM and HERB significantly damaged the aboveground vegetative organs of taro in 1996 (Fig.2 and Fig. 3).

The pattern of growth in corm dry weight was a typical S-shaped curve, whereas the shapes of growth curves in dry matter production of the aboveground vegetative organs varied with planting months (Fig. 3). The response of HI with time in taro decreased following planting and increased during the vigorous top-growth and rapid corm-bulking stages (Fig. 3). Thus, a three-phase piecewise linear function was used

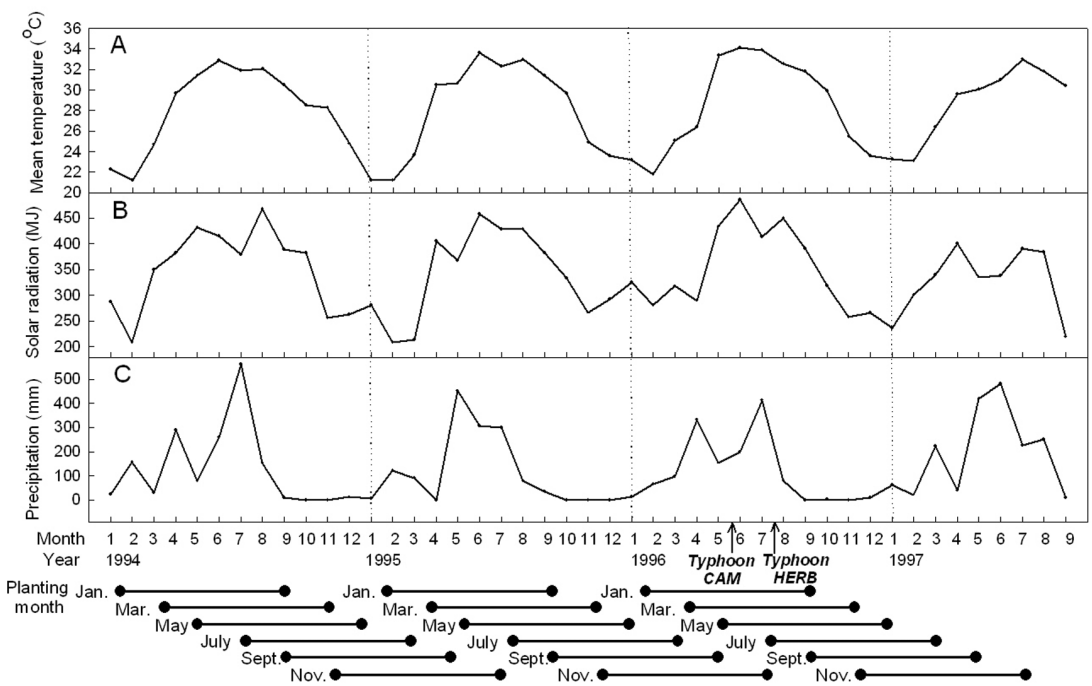

Fig. 2. Changes of daily mean temperature, monthly solar radiation and monthly precipitation at Taiwan Agricultural Research Institute during the 1994-1997 cropping seasons. (typhoons CAM, HERB caused significant disasters.)

to modeling the linear increase in HI. The response of HI was, however, sensitive to climatic factors and varied with planting month (Fig. 3).

There were only slight differences in temperature among years, and thermal time accumulation was nearly identical (Fig. 4). The parameter estimates of the three-phase piecewise linear functions fitted to HI data by using DAP and GDD after planting are listed in Table 1. All regressions were significant and all coefficients of determination (R^2 values) exceeded 0.91. Estimates of the square root of mean square of prediction difference were low for both DAP and GDD models. Piecewise linear functions based on either DAP or GDD fitted well.

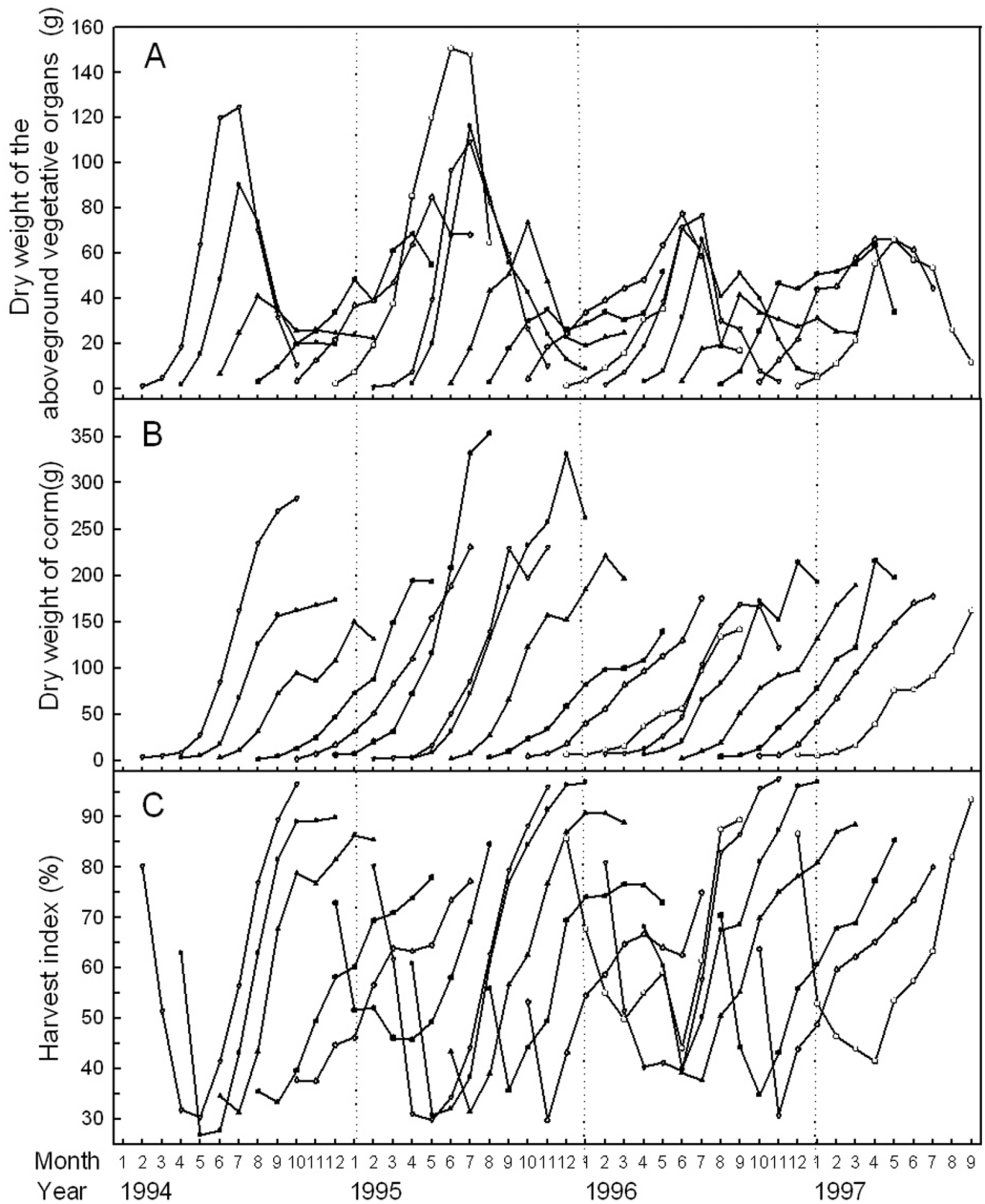

Fig. 3. Development of (A) dry weight of the aboveground vegetative organs, (B) dry weight of corm, and (C) harvest index.

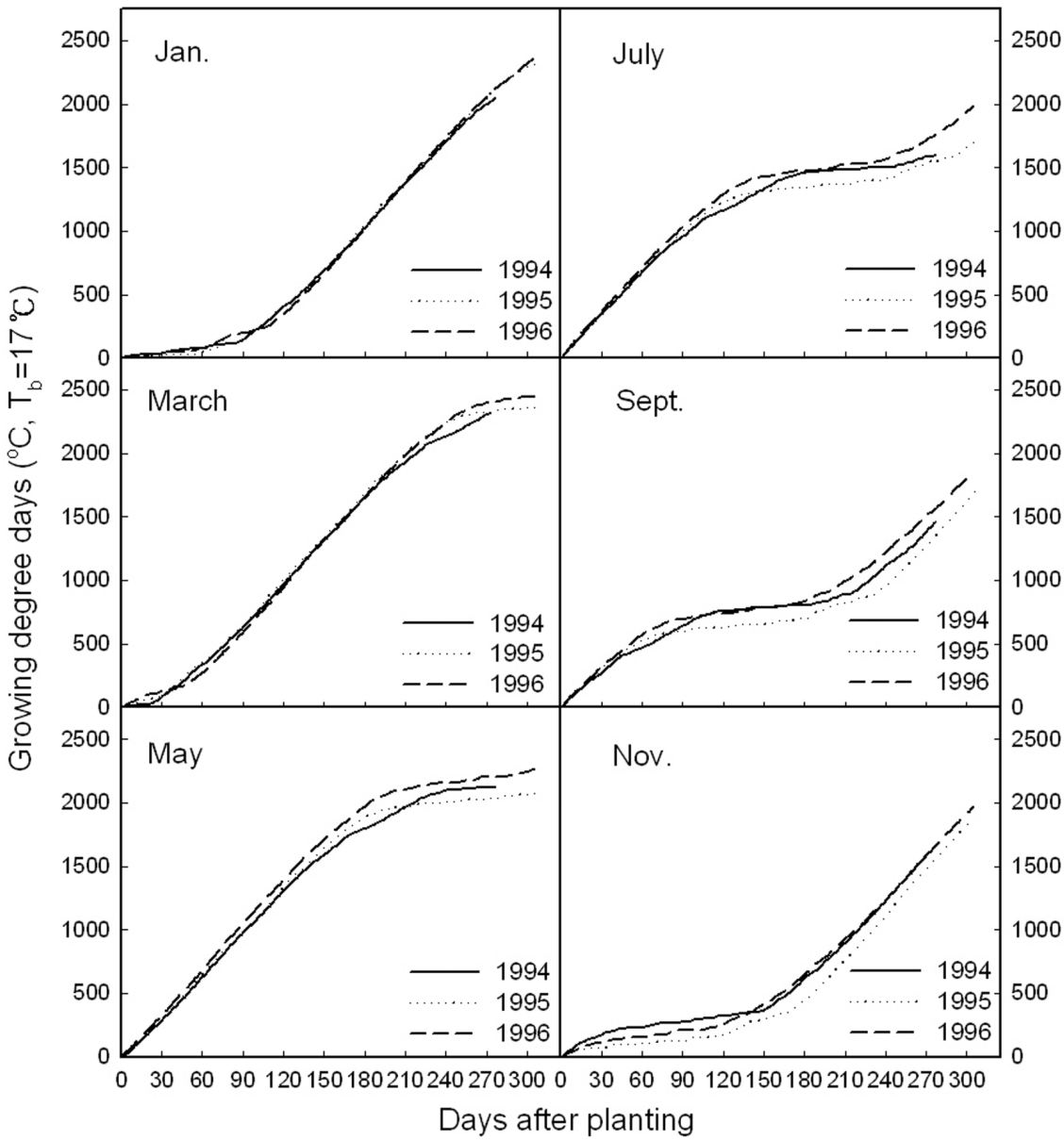

Fig. 4. Accumulation of growing degree days (GDD), with base temperature (T_b) of 17℃, during the growth of taro plants, 1994-1996.

The rate and duration of each phase in HI for different planting months are shown in Table 2. Because the response of linear increase in HI was most important for final HI (Lu *et al.* 1999), we focused on this linear increase phase. Variations in both rate and duration of linear increase were found among different planting months, regardless of whether DAP or GDD was used. The responses during the phase of linear increase were, however, more stable across years for the GDD model (Fig. 5). This indicated that the formula for GDD better explained the seasonal variation in linear increase of HI than the formula for DAP. Three-phase piecewise linear functions fitted to HI data for the GDD model are shown in Fig. 6.

Table 1. Parameter estimates of the three-phase piecewise linear functions fitted to harvest index (HI) in taro for each planting time using calendar days after planting (DAP) and growing degree days after planting (GDD).

	Jan.[1]			Mar.			May			July			Sept.			Nov.		
Estimate [3]	1[2]	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
DAP model																		
x_1	79	82	77	63	61	70	35	43	39	35	56	70	38	53	64	68	83	83
x_2	20	19	29	14	20	42	30	30	36	33	32	30	38	29	32	41	43	38
x_3	88	88	95	89	90	86	76	92	72	68	75	55	61	59	58	60	86	60
x_4	96	97	98	90	98	98	86	89	89	77	75	84	76	71	78	85	89	95
T_1	106	107	109	69	71	94	74	64	92	62	69	80	63	60	61	136	132	99
T_2	242	273	260	196	219	230	136	227	163	206	175	154	182	132	152	231	247	232
P>F	0.01	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	0.06	0.01	0.01
R^2	0.99	0.98	0.94	1.00	0.99	0.98	0.99	0.99	0.99	0.99	0.97	0.99	0.98	0.95	0.99	0.93	0.97	0.95
RMSPD	2.15	3.05	5.44	0.78	2.71	2.83	1.26	1.43	1.56	1.52	2.39	1.35	2.09	2.74	1.43	3.38	2.53	3.96
GDD model																		
x_1	75	76	72	63	61	69	35	43	39	36	56	71	38	53	64	70	86	87
x_2	18	17	30	15	20	41	30	30	36	32	27	27	37	30	28	44	48	42
x_3	87	87	95	89	76	76	74	65	81	79	79	75	61	63	61	60	87	60
x_4	96	96	95	90	97	96	85	91	89	78	73	86	78	71	80	85	89	94
T_1	201	195	252	416	458	638	800	713	1071	880	880	986	596	543	609	302	143	170
T_2	1667	2056	1954	1836	1740	1898	1449	1711	2149	1694	1445	1687	834	672	803	1121	1198	1160
P>F	0.01	<0.01	0.03	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.03	<0.01	0.02	<0.01	<0.01	0.03	<0.01	<0.01
R^2	0.98	0.98	0.92	1.00	0.99	0.98	1.00	0.99	0.99	0.98	0.91	0.97	0.94	0.96	1.00	0.96	1.00	0.98
RMSPD	3.41	3.59	6.51	0.74	2.47	2.48	1.37	2.52	1.92	2.19	4.37	2.74	3.33	2.48	0.69	2.70	0.64	2.32

[1] Planting month.
[2] Year cycle: 1, 1994; 2, 1995; and 3; 1996.
[3] x_1, x_2, x_3, x_4, T_1 and T_2, see Eq.[1]; RMSPD, square root of mean square of prediction difference.

Table 2. Responses (rate and duration) of each linear phase in harvest index (HI) of taro for each planting time using calendar days after planting (DAP) and growing degree days after planting (GDD).

		Jan.[1]			Mar.			May			July			Sept.			Nov.		
	Phase[3]	1[2]	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
DAP model																			
Rate, % /day	Lag	-0.81	-0.86	-0.62	-1.25	-1.00	-0.48	-0.10	-0.40	-0.06	-0.07	-0.64	-0.84	-0.01	-0.86	-1.02	-0.26	-0.40	-0.65
	Increase	0.50	0.42	0.44	0.59	0.47	0.32	0.74	0.38	0.52	0.24	0.40	0.33	0.20	0.42	0.28	0.20	0.38	0.17
	Maturity	0.23	0.25	0.06	0.01	0.09	0.16	0.08	-0.03	0.12	0.10	e-4	0.19	0.12	0.07	0.13	0.53	0.05	0.48
Duration, days	Lag	73	74	77	39	40	58	42	32	60	31	38	48	31	29	31	101	101	68
	Increase	136	166	150	127	148	136	62	162	71	144	106	74	118	72	91	95	115	133
	Maturity	35	34	45	77	87	78	141	79	141	99	132	151	121	176	151	46	57	73
GDD model																			
Rate, %/℃ degree day	Lag	-4e-3	-0.35	-0.19	-0.14	-0.12	-0.05	-0.01	-0.03	-4e-3	-0.01	-0.05	-0.07	-e-3	-0.10	-0.12	-0.24	-0.51	-0.80
	Increase	0.04	0.04	0.04	0.05	0.04	0.03	0.07	0.04	0.04	0.06	0.09	0.07	0.10	0.26	0.17	0.02	0.04	0.02
	Maturity	0.07	0.04	e-3	2e-3	0.04	0.04	0.02	0.07	0.07	-0.01	-0.02	0.04	0.02	0.01	0.02	0.05	4e-3	0.04
Duration, ℃ degree days	Lag	156	168	225	334	352	496	490	401	722	519	533	593	376	228	292	108	73	55
	Increase	1466	1861	1702	1421	1282	1260	649	998	1079	814	565	701	238	129	194	820	1055	990
	Maturity	387	266	408	483	619	547	675	367	120	146	273	300	931	1054	1036	538	684	811

[1] Planting month.
[2] Year cycle: 1, 1994; 2, 1995; and 3; 1996.
[3] Lag, the lag phase in HI; Increase, the linear increase in HI; Maturity, the maturity stage in HI; Rate, see Eq.[2]; Duration, see Eq. [3].

Final HI differed significantly among planting months (Table 3). Taro planted in January and March had the highest final HI, whereas taro planted in July and September had the lowest (Table 3). It was assumed that dry matter production in the aboveground vegetative organs was increased by high temperature and high solar radiation during the vigorous top-growth stage for January and March crops and by a higher amount of N transferred to the corm (Chan *et al.* 1999, Wei *et al.* 1999). This resulted in greater source efficiency and rapid corm bulking, which in turn, favored yield at maturity. On the other hand, declining temperature and lower solar radiation during the vigorous top-growth stage for July and September crops reduced production of photosynthate in the above-ground vegetative organs. Less assimilate was transferred to the corm during this stage (Wei *et al.* 1999), and dry matter and N accumulation in the above-ground vegetative organs still increased during the rapid corm-bulking stage (Chan *et al.* 1999). This resulted in poor yield at maturity. The May and November crops, with intermediate corm yield, showed similar patterns in the accumulation of dry matter and N. The accumulation rates for May and November crops were lower than those for the January crop (Chan *et al.* 1999). These results showed that final HI was closely related with plant performance during the phase of linear increase in HI. Although typhoons CAM and HERB in 1996 caused serious damages in taro leaves for the January and March crops, the performance of linear increase in HI remained little change.

When using the linear increase phase to predict final HI, the formula based on DAP was less efficient than the one based on GDD (Table 3). In the DAP model, no significant differences were found in the duration of linear increase among planting months, and the effect of seasonal variation on final HI could not be explained satisfactorily by the seasonal differences in the rate of linear increase. In the GDD model, the January and March crops had a longer duration of linear increase that favored final HI. Although the September crop had the highest rate of linear increase, its final HI was the lowest among treatments. This was principally caused by the short duration of linear increase. Both the lower rate and shorter duration of linear increase reduced the final HI for the July crop. There were no significant differences in the rate of linear increase among the May, November, and January crops; but the shorter duration in linear increase resulted in lower final HI for taro plants planted in May and November. There was a clear relationship between weather and linear increase in HI for the GDD model. Therefore, the GDD model was superior to DAP model for explaining the seasonal variation of HI in taro. We anticipate that use of the three-phase piecewise linear function based on GDD may lead to the recognition of phenological responses to seasonal variation in taro.

Table 3. Final harvest index (HI) and the responses (rate and duration) of linear HI increase in taro planted in different months averaged across 3 years.

Planting month	Final HI	DAP [1] model		GDD [2] model	
		Rate	Duration	Rate	Duration
		%/day	days	%/℃degree day	℃ degree days
Jan.	96.7 a [3]	0.454 ab	151 a	0.039 b	1676 a
Mar.	94.9 ab	0.462 ab	137 a	0.041 b	1321 b
May	87.9 c	0.545 a	98 a	0.048 b	908 c
July	78.7 d	0.325 ab	108 a	0.072 b	693 c
Sept.	75.6 d	0.300 b	94 a	0.178 a	187 d
Nov.	89.5 bc	0.248 b	114 a	0.025 b	955 c
LSD(0.05)	5.8	0.224	58	0.062	280

[1] DAP, calendar days after planting.

[2] GDD, growing degree days after planting.

[3] Within columns, means followed by the same letters (s) are not significantly different based on Fisher's protected LSD at $P<0.05$.

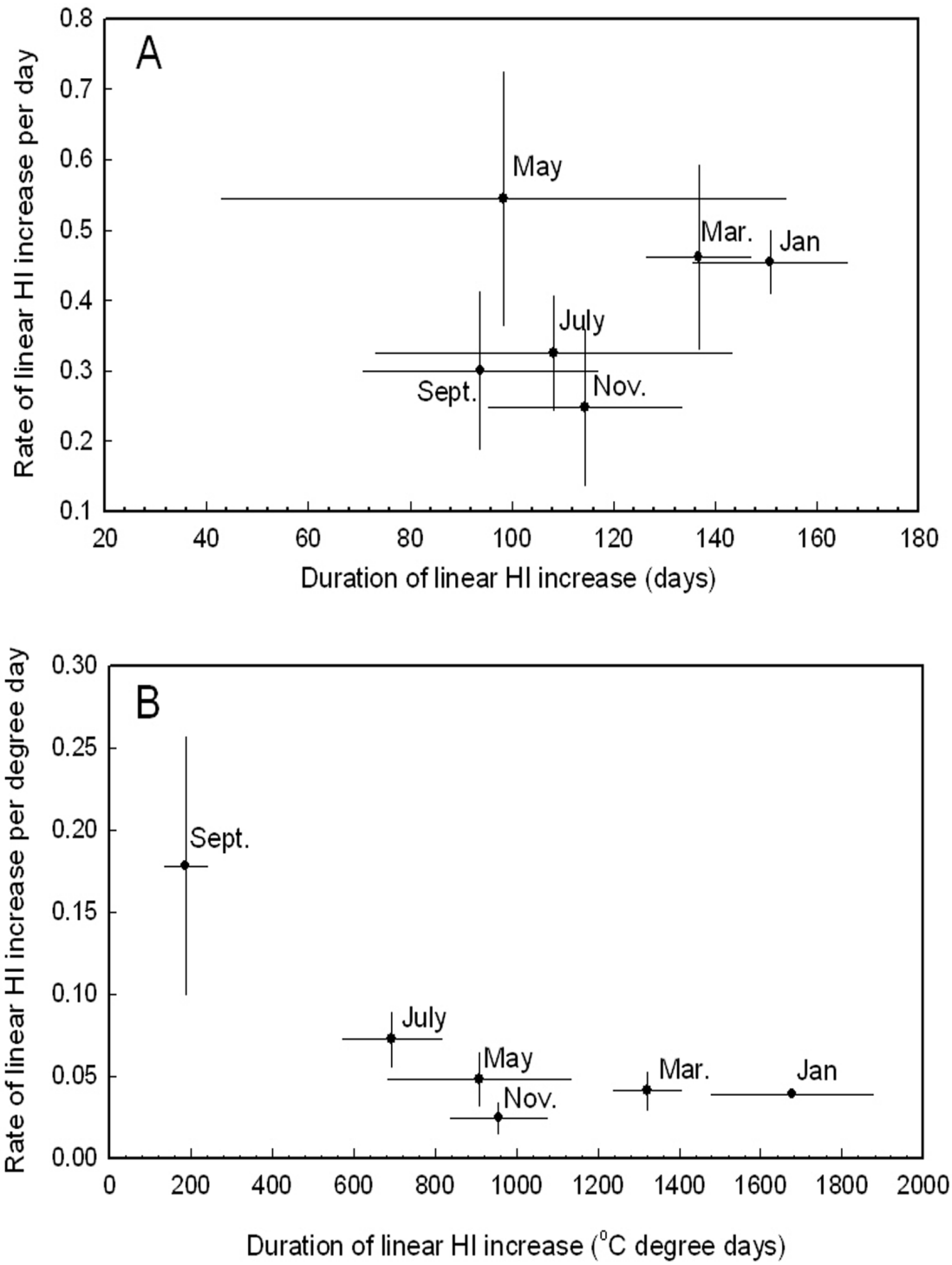

Fig. 5. Rate and duration of linear increase in harvest index (HI) of wetland taro planted in different months of the year as calculated from piecewise linear functions based on (A) calendar days (GDP) and (B) growing degree days after days (GDD). (● represents mean across 3 years, and error bars represent for 2 x standard error among years.)

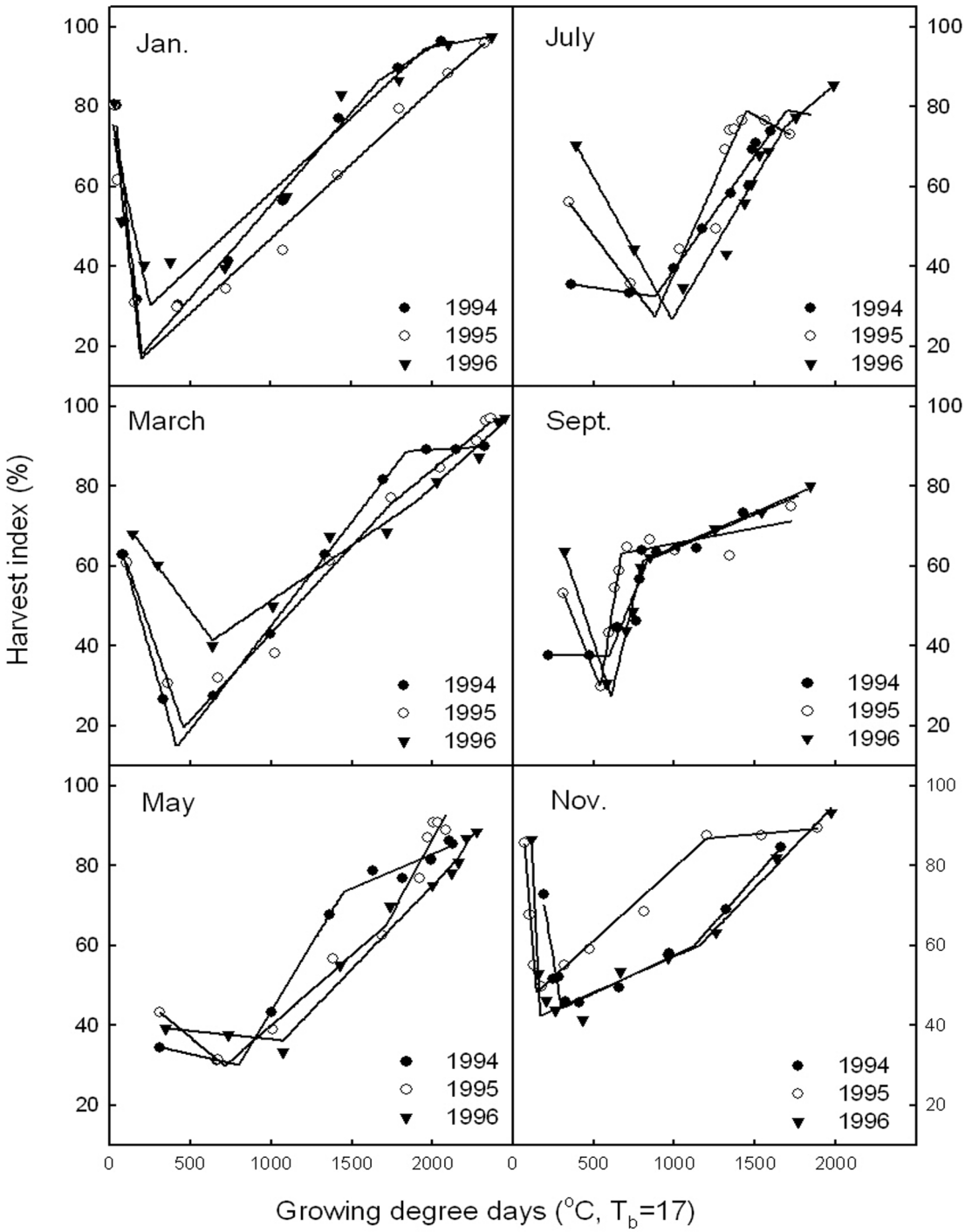

Fig. 6. Relationship of growing degree days after planting (GDD) to harvest index (HI) of wetland taro planted in different months of the year. (●, ○ and ▼ represent observed values, and solid line represents fitted curve using three-phase piecewise linear function.)

ACKNOWLEDGMENTS

This work was supported by the National Science Council, Taiwan (ROC) with grant no. NSC 85-2321-B055-005, NSC 86-2321-B055-002 and NSC 87-2321-B005-003.

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